Monte Carlo Simulations
for NLO Chargino Production at the ILC

Tania Robens [*]

RWTH Aachen - Institut für Theoretische Physik E
52056 Aachen - Germany

We present an extension of the Monte Carlo Event Generator `WHIZARD` which includes chargino production at the ILC at NLO. We include photons using both a fixed order and a resummation approach. In the latter, leading higher order corrections are automatically included. We present results for cross sections and event generation for both methods [1].This is an updated version of the results presented in [2].

1   Introduction

In many GUT models, the masses of charginos tend to be near the lower edge of the superpartner spectrum, and they can be pair-produced at a first-phase ILC with c.m. energy of 500 GeV. The precise measurement of their parameters (masses, mixings, and couplings) is a key for uncovering the fundamental properties of the MSSM [3]. Regarding the experimental precision at the ILC, off-shell kinematics for the signal process, the reducible and irreducible backgrounds [4], and NLO corrections need to be included. We here present the inclusion of NLO chargino production where corrections can be in the percent regime.

2   Chargino production at LO and NLO

The total fixed-order NLO cross section is given by

$$\sigma_{\mathrm{tot}}(s, m_e^2) = \sigma_{\mathrm{Born}}(s) + \sigma_{\mathrm{v+s}}(s, \Delta E_\gamma, m_e^2) + \sigma_{2 \to 3}(s, \Delta E_\gamma, m_e^2), \tag{1}$$

where s is the cm energy, m_e the electron mass, and ΔE_γ the soft photon energy cut dividing the photon phase space. The 'virtual' contribution σ_{v} is the interference of the one-loop corrections [5] with the Born term. The collinear and infrared singularities are regulated by m_e and the photon mass λ, respectively. The dependence on λ is eliminated by adding the soft real photon contribution $\sigma_{\mathrm{s}} = f_{\mathrm{soft}}\, \sigma_{\mathrm{Born}}(s)$ with a universal soft factor $f_{\mathrm{soft}}(\frac{\Delta E_\gamma}{\lambda})$ [6]. We break the 'hard' contribution $\sigma_{2 \to 3}(s, \Delta E_\gamma, m_e^2)$, i.e., the real-radiation process $e^- e^+ \to \tilde{\chi}_i^- \tilde{\chi}_j^+ \gamma$, into a collinear and a non-collinear part, separated at a photon acollinearity angle $\Delta\theta_\gamma$ relative to the incoming electron or positron. The collinear part is approximated by convoluting the Born cross section with a structure function $f(x; \Delta\theta_\gamma, \frac{m_e^2}{s})$ [7]. The non-collinear part is generated explicitly.

The total fixed order cross section is implemented in the multi-purpose event generator `O'Mega`/`WHIZARD` [8, 9] using a 'user-defined' structure function and an effective matrix element $|\mathcal{M}_{\mathrm{eff}}|^2$ which contains the Born part, the soft-photon factor and the Born-1 loop interference term. In the soft-photon region this approach runs into the problem of negative
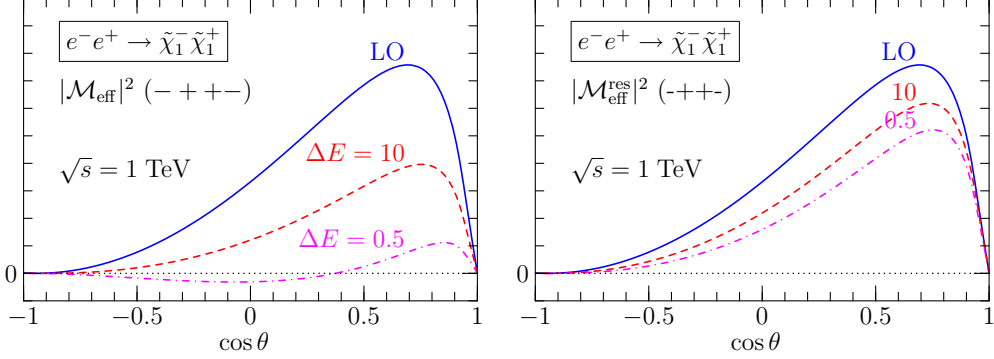
Figure 1: θ -dependence of effective squared matrix element ($\sqrt{s} = 1$ TeV).Left figure: fixed order effective matrix element; right figure: effective matrix element with the one-photon ISR part subtracted. Solid line: Born term; dashed: including virtual and soft contributions for $\Delta E_\gamma = 10$ GeV; dotted: same with $\Delta E_\gamma = 0.5$ GeV. $\Delta\theta_\gamma = 1°$.

event weights [10]: for some values of θ, the $2 \to 2$ part of the NLO-corrected squared matrix element is positive definite by itself only if ΔE_γ is sufficiently large, cf Fig. 1. To still obtain unweighted event samples, an ad-hoc approach is to simply drop events with negative events before proceeding further.

Negative event weights can be avoided by resumming higher-order initial radiation using an exponentiated structure function f_{ISR} [11]. In order to avoid double-counting in the combination of the ISR-resummed LO result with the additional NLO contributions [5], we have subtract from the effective squared matrix element the soft and virtual photonic contributions that have already been accounted for in $\sigma_{\text{s+v}}$. This defines $|\mathcal{M}_{\text{eff}}^{\text{res}}|^2 = |\mathcal{M}_{\text{eff}}|^2 - 2f_{\text{soft,ISR}} |\mathcal{M}_{\text{Born}}|^2$ which is positive for even low ΔE_γ cuts for all values of θ (cf Fig. 1), such that unweighting of generated events and realistic simulation at NLO are now possible in all regions of phase-space. Convoluting this with the resummed ISR structure function for each incoming beam, we obtain a modified $2 \to 2$ part of the total cross section which also includes soft and collinear photonic corrections to the Born/one-loop interference. This differs from the standard treatment in the literature (cf eg. [5]) where higher order photon contributions are combined with the Born term only ("Born+"). The complete result contains the hard non-collinear $2 \to 3$ part convoluted with the ISR structure function:

$$\sigma_{\text{res,+}} = \int^{\Delta(E,\theta)} dx_i\, d\Gamma_2\, f_{\text{ISR}}^{(e^+)}(x_1) f_{\text{ISR}}^{(e^-)}(x_2)|\mathcal{M}_{\text{eff}}^{\text{res}}|^2 + \int_{\Delta(E,\theta)} dx_i\, d\Gamma_3\, f_{\text{ISR}}^{(e^+)}(x_1) f_{\text{ISR}}^{(e^-)}(x_2)|\mathcal{M}^{2\to3}|^2 \tag{2}$$

3   Results

Fig. 2 compares the ΔE_γ dependence of the numerical results from the semianalytic fixed-order calculation with the Monte-Carlo integration in the fixed-order and in the resummation schemes. The fixed-order Monte-Carlo result agrees with the semianalytic result as long as the cutoff is greater than a few GeV but departs from it for smaller cutoff values because here, in some parts of phase space, $|\mathcal{M}_{\text{eff}}|^2 < 0$ is set to zero. The semianalytic fixed-order
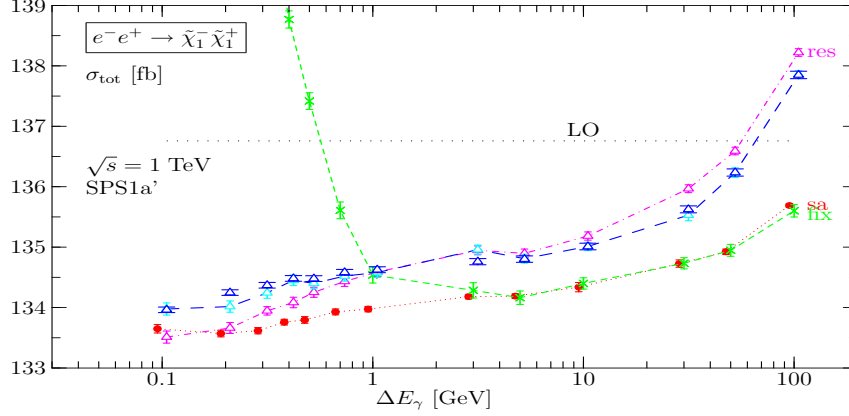
Figure 2: Total cross section dependence on ΔE_γ: 'sa' (dotted) = fixed-order semianalytic result; 'fix' (dashed) = fixed-order Monte-Carlo result; 'res' (long-dashed) = ISR-resummed Monte-Carlo result; (dash-dotted) = same but resummation applied only to the $2 \to 2$ part. $\Delta\theta_\gamma = 1°$. LO: Born cross section.

result is not exactly cutoff-independent, but exhibits a slight rise of the calculated cross section with increasing cutoff (breakdown of the soft approximation). For $\Delta E_\gamma = 1$ GeV (10 GeV) the shift is about 2 permil (5 permil) of the total cross section. The fully resummed result shows an increase of about 5 permil of the total cross section with respect to the fixed-order result which stays roughly constant until $\Delta E_\gamma > 10$ GeV. This is due to higher-order photon radiation.

In Fig. 3 we show the binned distribution of the chargino production angle obtained using a sample of unweighted events. It demonstrates that NLO corrections (which, for total cross sections, are in the percent regime and can reach 20% at the threshold) are important and cannot be accounted for by a constant K factor. Figure 4 shows the magnitude of second and higher order photonic effects in different schemes. Resummation effects are clearly in the percent regime and cannot be neglected. For $\sqrt{s} > 500$GeV, the convolution of the interference term with f_{ISR} additionally changes the sign of the higher order corrections. For more details, cf. [12, 13].

4   Conclusions

We have implemented NLO corrections into the event generator `WHIZARD` for chargino pair-production at the ILC with several approaches for the inclusion of photon radiation. A careful analysis of the dependence on the cuts ΔE_γ, $\Delta\theta$ reveals uncertainties related to higher-order radiation and breakdown of the soft or collinear approximations. To carefully choose the resummation method and cutoffs will be critical for a truly precise analysis of real ILC data.The version of the program resumming photons allows to get rid of negative event weights, accounts for all yet known higher-order effects, allows for cutoffs small enough that soft- and collinear-approximation artefacts are negligible, and explicitly generates photons where they can be resolved experimentally. Corrections for the decays of charginos and non-factorizing corrections are in the line of future work.
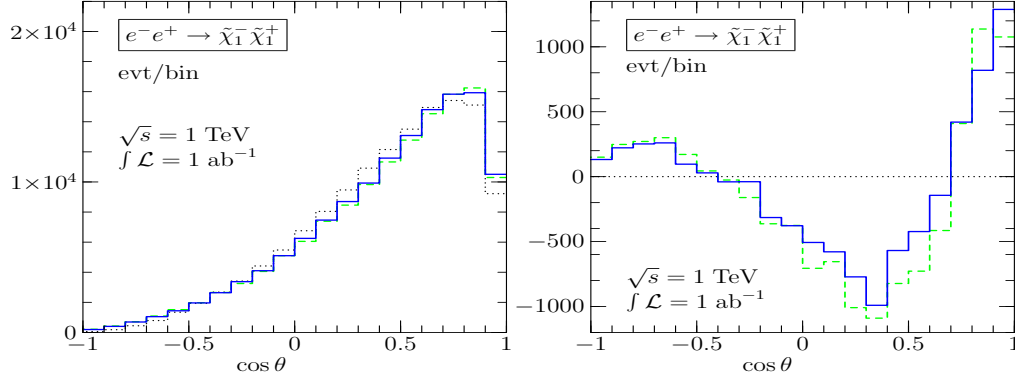
Figure 3: Polar scattering angle distribution for an integrated luminosity of 1 ab^{-1} at $\sqrt{s} = 1$ TeV. Left: total number of events per bin; right: difference w.r.t. the Born distribution. LO (dotted) = Born cross section without ISR; fix (dashed) = fixed-order approach; res (full) = resummation approach. Cutoffs: $\Delta E_\gamma = 3$ GeV and $\Delta\theta_\gamma = 1°$.
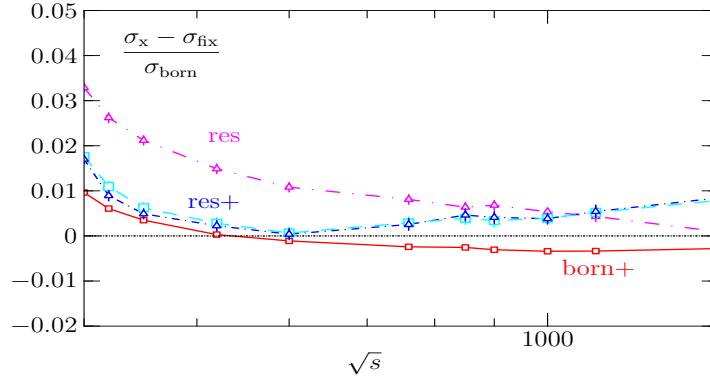

Figure 4: Relative higher-order effects for different methods: (magenta, long dash dotted) = σ_{res}, (blue/ cyan and dash-dotted/ dashed) = $\sigma_{\text{res+}}$, and (red, solid) = $\sigma_{\text{Born+}}$ vs σ_{Born}.

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